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SEVENTH QUARTERLY PROGRESS REPORT

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UNDER THE TECHNICAL SUPERVISION
OF THE ATOMICS BRANCH OF
THE APPLIED PHYSICS DIVISION
U. S. ARMY SIGNAL RESEARCH AND
DEVELOPMENT LABORATORIES
AT FORT MONMOUTH

by
M. N. HIRSH
P. N. EISNER

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AN EXPERIMENTAL INVESTIGATION OF
THE EFFECTS OF RADIATION ON THE PROPOGATION
OF ELECTROMAGNETIC SIGNALS IN AIR.

7 —SEVENTH QUARTERLY PROGRESS REPORT 11.00

Prepared under
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of The Atomics Branch of
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10) by

M. N. Hirsh
P. N. Eisner.

11 31 March 1963, 12.00 p. 1.00

THE G. C. DEWEY CORPORATION
202 East 44th Street
New York 17, New York

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I. INTRODUCTION

The present report covers work performed during the period 1 January to 31 March 1963. It begins with a description of modifications made to the experimental equipment to permit the measurement of time-dependent ionization phenomena. The results of transient measurements in oxygen and $N_2 - O_2$ mixtures using these techniques is then presented. A detailed calculation of the role of diffusion in transient ionization phenomena has been started and is discussed in the report. The report closes with a description of the proposed work for the next quarter.

During the period covered by the report, the authors delivered a paper at the New York meeting of the American Physical Society, ⁽¹⁾ in which the techniques of the present program, together with preliminary data on oxygen loss processes, were discussed.

(1) M. N. Hirsh and P. N. Eisner, Bull Am. Phys. Soc. II, vol. 8, p. 58 (1963)

II. EXPERIMENTAL EQUIPMENT

A. RF Circuit

In Section III, a series of transient experiments will be described which utilize the electron beam switch described in previous reports. However the rf system described in previous reports has been arranged to give measurements in the steady state only. For these experiments the measuring circuits were modified through the use of timing and triggering circuits to enable rf measurements to be made as a function of time after the electron beam turn-on.

A block diagram of this system is shown in Figure 1; the timing sequence of this system is shown in Figure 2. All operations within this system are periodic, with a cyclic rate determined by the sweep frequency of a tektronix Model 545 oscilloscope, whose sawtooth output triggers the Van de Graaff's electron beam switch through the relay circuit explained in the Sixth Quarterly Report. The oscilloscope also has an adjustable delayed sweep. The trigger from this delayed sweep initiates the sweep of another sawtooth generator; the output of which is used in two ways, first to drive the external sweep mechanism of the read-out scope, a type 562, Tektronix Dual-Beam Oscilloscope and second, to sweep the frequency of the 0-5 mcps oscillator used as the modulation oscillator in the rf bridge.

In Figure 2, Trace 3 represents the sawtooth which sweeps the frequency of the modulation oscillator. When this oscillator is at the correct frequency for cavity resonanace, a pip will be seen on channel A of the dual beam scope. This is shown in Figure 2 on Trace 4. The time at which this occurs is determined by reading time $T_3 - T_2$ from the trace on channel A of the dual beam scope

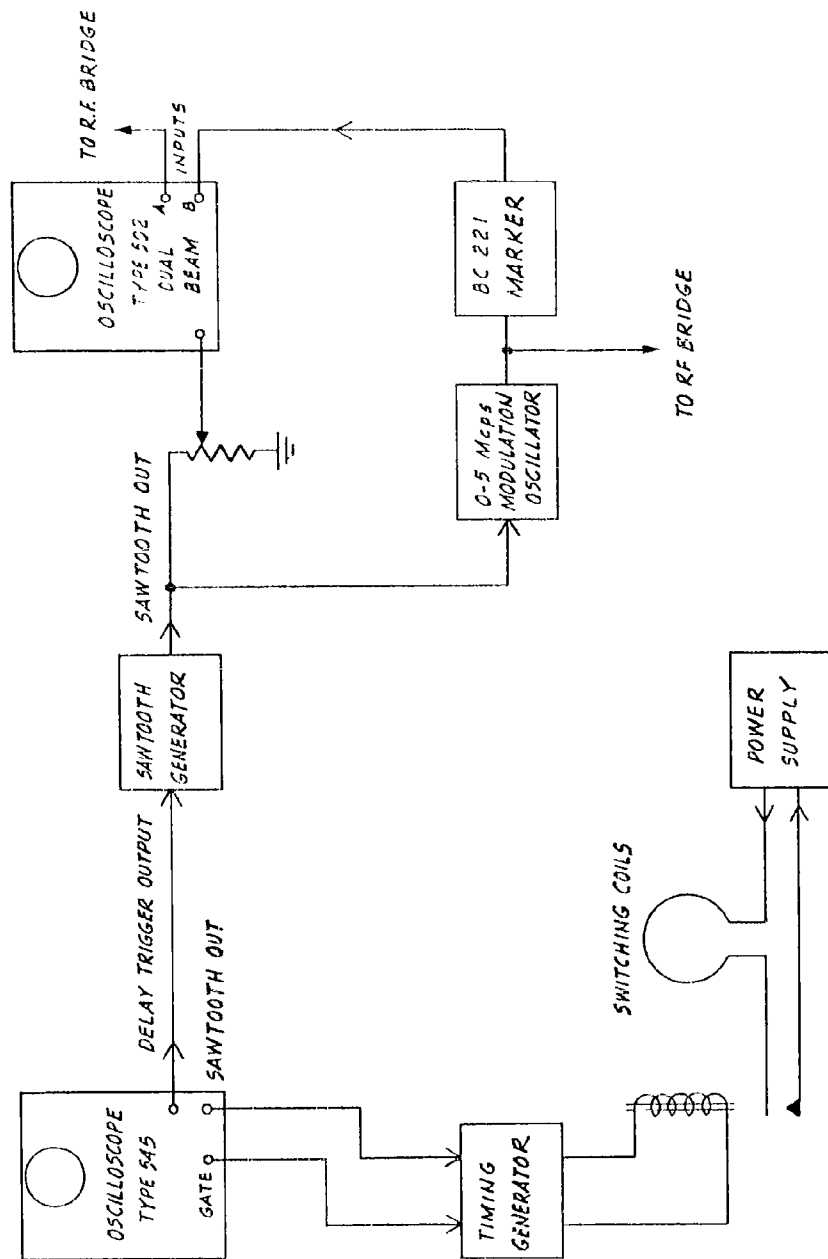


FIGURE 1
BLOCK DIAGRAM OF TIMING CIRCUITS FOR
TRANSIENT MEASUREMENTS

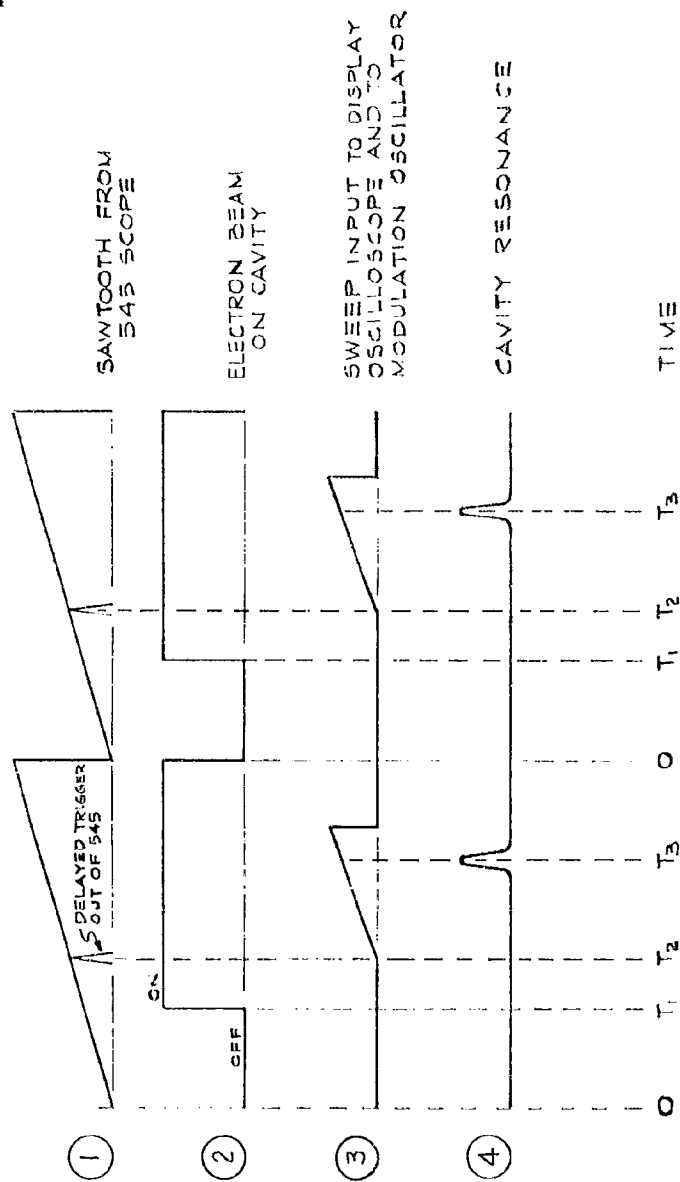


FIGURE 2
TIMING SEQUENCE FOR TRANSIENT MEASUREMENTS

and adding to that the delayed trigger time T_2 . Time T_1 can be determined by moving the delayed trigger until the turn-on of the electron beam is observed.

The system described above has a time resolution capability of about one millisecond which is adequate for timing the transients which have been observed so far. The accuracy and time resolution is mainly determined by the stability and speed of the electron-beam switching mechanism which is a relay actuated device. Improvements could be made by using an all-electronic switch and coils of lower inductance to switch the beam faster.

B. Foil Diffuser

On page 4 of the Fifth Quarterly Report it was reported that "further work on the beam diffusion problem was deferred until after the air and oxygen experiments were completed so that any information learned from these experiments could be incorporated into the next equipment changes." That time has now come.

Several important points have been learned from the results of the steady-state experiments, which have a bearing on the primary electron diffusion. First, the net ionization observed at low pressures in oxygen cannot be related to fundamental mode ambipolar diffusion if a homogeneous distribution of primary electrons is assumed. This point will be explained in Section IV. Second, at high pressures in oxygen where ionization measurements point to a three body electron attachment as the dominant electron removal process, the numerical value of that coefficient depends on the net primary (high energy) electron current traversing the microwave cavity. Since direct attempts to measure this current failed (cf Sixth Quarterly Report), assumptions concerning the angular distribution of scattering in beryllium foils must be made in order to calculate the percentage of the beam which enters the cavity.

However, these assumptions, which will be explained in this section, do not lead to the accepted value for the three body attachment coefficient. The third point to be considered is an experiment described in the Fifth Quarterly Report which indicated that even with .024 inches of beryllium foil, the electron beam only covered an area corresponding to a diameter of 2 to 3 feet at the cavity face. The cavity face has a diameter of 4 feet, so that there is not a homogeneous distribution of electrons across its face. Thus during this quarter measurements were made of the beam current passing through the foil and collimator in order to determine the electron beam distribution and the actual percentage of the beam transmitted by the foil and collimator. Figure 3 schematically illustrates the method used.

- A - SWITCHING COILS
- B - FOIL DIFFUSER
- C - COLLIMATOR
- D - INSULATING FLANGE
- E - FARADAY CUPS

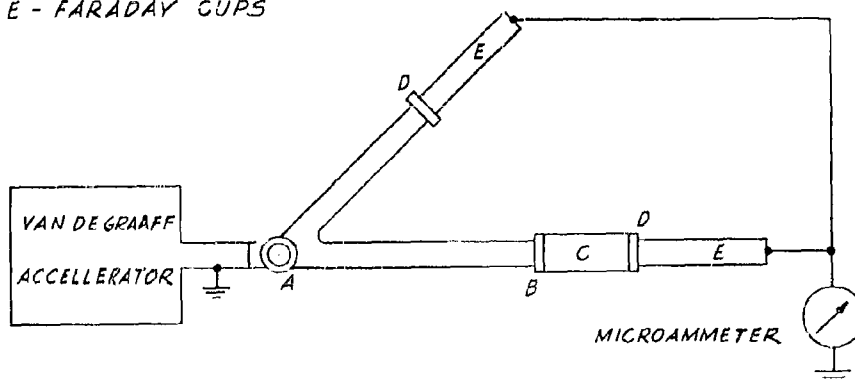


FIGURE 3
FOIL SCATTERING CALIBRATION TECHNIQUE

A section of 2" diameter beam tube between the Van de Graaff and the beam switching section was removed, leaving room for a long faraday cup after the collimator. The electron beam is alternately switched between the two faraday cups. Immediately it was discovered that much more current was collected in the faraday cup behind the collimator than a calculation based upon this test geometry indicated was possible. It was believed that this was either due to poor collimation following the scattering foil or to porous beryllium foil, resulting in under estimation of the scattering angle. Titanium foil 1.24.05 mils thick was substituted for the beryllium. This foil also appeared to scatter the electrons less than the calculated amount. The density of the titanium foil was measured, and found to be 4.5 gm/cm^3 , in excellent agreement with published values; this value was used in the scattering calculation itself. Therefore poor electron collimation due to glancing of electrons off the walls of the collimator was the probable fault. A new collimator was designed and tested which eliminated this problem. With the new collimator, 21.8% of the beam was collected in the faraday cup; this compares with a calculated percentage for this geometry of 21.2% for Titanium foil 1.2×10^{-3} inches thick. However, the five beryllium foils used in previous experiments transmitted 58.5% with the new collimator, as compared with the calculated transmission for the .024" thickness of 44.8%. This discrepancy still remains unexplained. Nevertheless, a beam current calibration for the foils was obtained. For a gaussian angular scattering distribution, the titanium foil will produce a distribution of primary electron across the cavity face uniform to within 5% in flux.

The calculation of the foil scattering distribution proceeds as follows. The mean scattering angle as a function of electron energy E and the composition of the scattering foil is*

* D. M. Ritson, Techniques of High Energy Physics, pg. 9, Interscience, N. Y. (1961)

$$(1) \quad \langle \theta^2 \rangle \simeq \left(\frac{21}{E} \right)^2 X,$$

where X is the distance in units of radiation length. For Be, X is 67gm/cm²; for titanium it is 16.6gm/cm². These have been calculated from

$$(2) \quad \frac{1}{X_0} = 1.37 \times 10^{-3} \frac{Z(Z+1)}{A} \log_e \frac{183}{3\sqrt{Z}} \text{ gm/cm}^2.$$

If the Gaussian scattering assumption is correct, then the standard

deviation $\sigma = \sqrt{\frac{\langle \theta^2 \rangle}{2}}$. The percentage of the beam transmitted

in a given angle can then be found from tables of the normal distribution.

C. Gas Handling System

In the past quarter, the gas handling system was modified to include 12 one-liter flasks. These were used up during this quarterly report period and were replaced by 100-liter cylinders of research grade oxygen and nitrogen. This is nominally the same purity gas as contained in the glass flasks but the gas has not been mass analyzed. One liter of gas at atmospheric pressure fills the cavity to a pressure of 1 Torr; in order to experiment at higher pressures conveniently the quantity of gas available had to be increased beyond the capacity of the one-liter flasks.

Bakeable pyrex Hastings vacuum gauges were inserted directly into the glass portion of the gas handling system (Figure 4). One gauge measures pressure in the range 0-100 microns; the other is used in the range 0-20 Torr. These gauges are calibrated for air and must therefore be calibrated against an absolute gauge for other gases or mixtures. However once this calibration has been done these gauges allow gas pressure measurements without the possibility of contaminating the sample gas in the cavity.

Neither the gas flow regulators nor the metal-to-glass seals in this system are bakeable, therefore this gas handling system is an interim design to permit high pressure measurements in the cavity. At the same time it will be learned whether the gas in the metal cylinders gives the same results as that in the glass flasks, so that a bakeable system can be built around the 100-liter cylinders in the future.

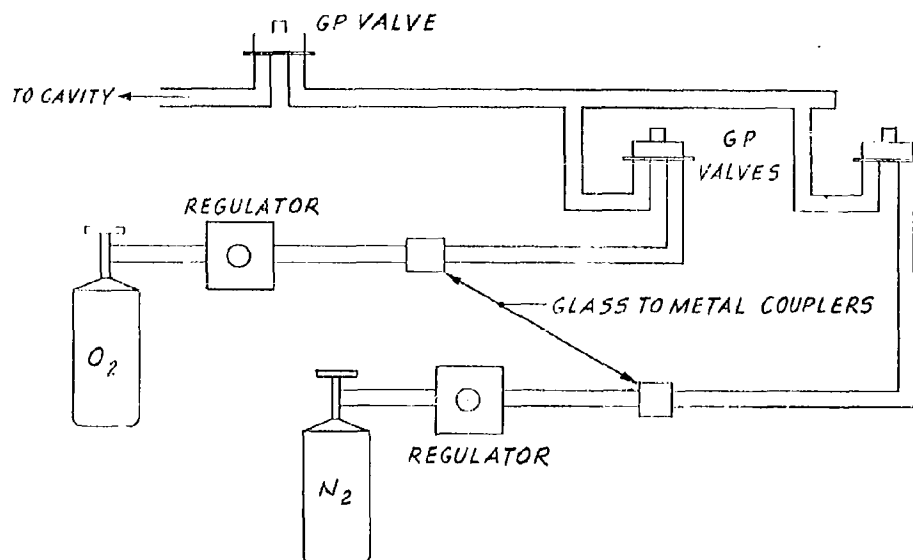


FIGURE 4
GAS HANDLING SYSTEM

III. TRANSIENT MEASUREMENTS IN OXYGEN

A. Photographic Technique

Transient measurements were made in oxygen, which were designed to observe the onset of diffusion in an effort to explain the behavior of the low pressure, diffusion dominated, steady-state ionization. These experiments used the Be foil diffuser. The technique used was to tune the rf oscillator to the cavity resonant frequency and then switch the electron beam onto the cavity. The result was that, as the cavity shifted frequency due to the presence of free electrons, the output signal from the bridge as observed on the oscilloscope would change as shown in Figure 5.

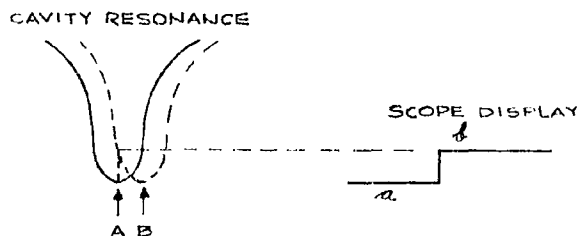


FIGURE 5

During the time when there is no electron beam in the cavity, the cavity resonance frequency is at A, yielding a straight line at amplitude "a" on the scope. The electron beam causes a frequency shift of the cavity from A to B which changes the observed amplitude on the scope from "a" to "b", because the oscillator frequency remains at A. Figure 6 is a reproduction of a photograph taken of the oscilloscope face during the turn-on of the electron beam. The important feature of these data is the rapid change in frequency immediately after the turn-on, followed by a slow change in the

opposite direction. The beam remains on the cavity during this experiment, so that a final frequency shift corresponding to the equilibrium value of ionization is seen, which is the same frequency measured in steady-state experiments. A reasonable interpretation of the phenomenon described above is that the slow shift in cavity frequency to an equilibrium value is due to diffusion of electrons and ions to the walls of the cavity until the diffusion process (which is the slowest loss process in the cavity) comes to equilibrium. Accordingly this transient phenomena was observed photographically for three pressures of oxygen, 0.11 Torr, 0.07 Torr, and 0.035 Torr. The decay of the slow transient was found to be an exponential function of time; the decay time was a linear function of pressure:

$$\tau \text{ (Seconds)} = 1.9 \times 10^3 p \text{ (Torr)}.$$

This yields a constant $D_{ap} = 120 \text{ Torr-cm}^2/\text{sec}$ assuming the decay is due to ambipolar diffusion proceeding in the fundamental mode.

However, a D_{ap} of 120 does not explain the low values of equilibrium ionization observed in both the steady-state experiments and in the transient experiments. This point was made before in the Sixth Quarterly report with respect to the steady-state experiments. The possible reasons for the discrepancy in numbers between an apparent measurement of the diffusion decay time, and the diffusion decay time required to produce the measured equilibrium ionization will be discussed in Section IV.

Photographs were also taken of the shut-off of the electron beam which showed a decay time similar to the rise time at

the beam turn-on (see Figure 6). The time constants involved are on the order of a few milliseconds but were very difficult to measure accurately with this technique. The time constant associated with the shut-off is of great importance, however, since it gives directly a value for the total electron loss frequency. This can then be compared with the value calculated from the steady state data by

$Kp_i = \gamma_L N$, where K is the production term and γ_L is the loss frequency.

B. Electronic Technique

The photographic work described above was difficult to interpret quantitatively. Thus measurements were made on transient phenomena in oxygen using the new rf system described in Section IIA and using the titanium foil diffuser. From Figure 6 with the assumption of an exponential decay of frequency versus time,

$$(1) \quad f = (f_0 - f_1)e^{-t/\tau} + f_1, \text{ or}$$

$$(2) \quad \Delta f = f - f_1 = (f_0 - f_1)e^{-t/\tau}.$$

Taking logarithms of both sides,

$$(3) \quad \log \Delta f = \log(f_0 - f_1) - t/\tau$$

Figure 7 is a plot of the slow (diffusion) transient in oxygen at 0.1 Torr using the time resolving rf circuits which shows reasonable agreement with the straight line predicted by equation (3). As indicated in Figure 7, the straight line fit to the data yields a calculated value of 101 Torr-cm²/sec for D_{ap} in agreement with estimates from the photographs. At a pressure of .05Torr, the measured D_{ap} was 66.3 Torr-cm²/sec which is not in agreement with theory or the earlier photographic measurements.

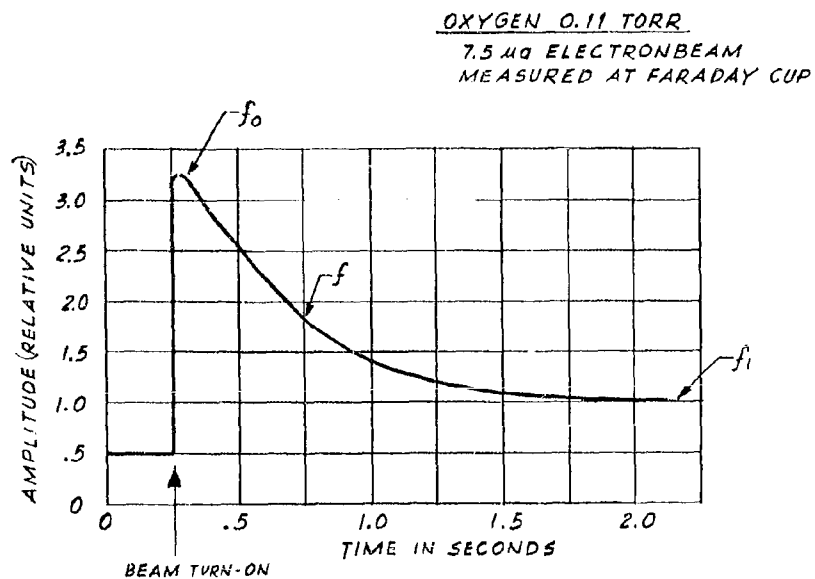
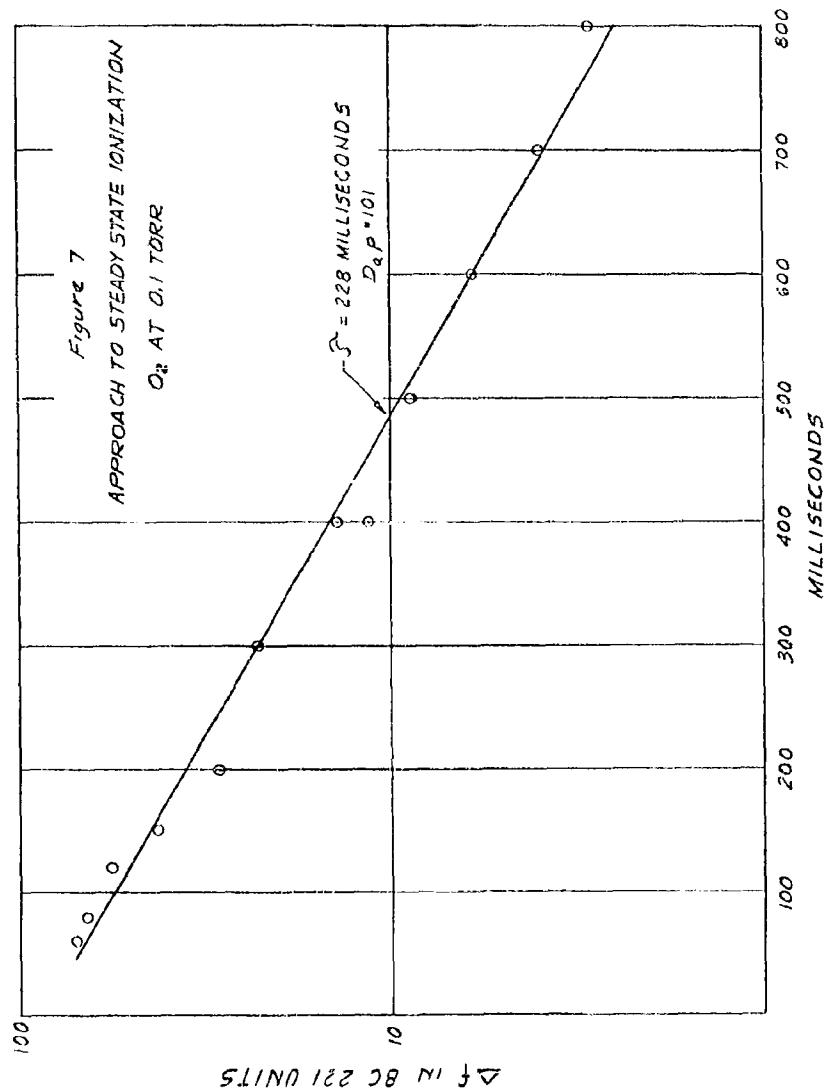


FIGURE 6
TRANSIENT WAVE SHAPE OBTAINED
PHOTOGRAPHICALLY



A summary of oxygen transient measurements is presented below:

| <u>Date</u> | <u>Pressure Torr</u> | <u>Beam Current Faraday cup</u> | <u>$\Delta f/I$ Equilibrium Slope</u> | <u>n_{ap}</u> |
|-------------|--------------------------|-------------------------------------|--|----------------------------|
| March 15 | 0.102 | 97.8 ua | 0.78 | 105 |
| March 18 | 0.010 | 150 ua | ? | ? |
| March 19 | 0.050 | 30 ua | 0.27 | 66.3 |
| March 25 | 0.100 | 50 ua | 0.68 | 101 |
| March 28 | 0.102 | 150 ua | 0.76 | ? |

The beam current was measured at the faraday cup in the upper arm of the beam switch; a titanium foil 1.2 mils thick was used to diffuse the beam into the cavity (see Section II-B). The question marks indicate that a measurement could not be made due to experimental difficulties or malfunction.

C. Summary of Results of Oxygen Experiments

Previous measurements of equilibrium ionization in oxygen at 0.1 Torr pressure resulted in a "slope", $\Delta f/I$ of 1.7 Kcps/ μ a (c.f. Sixth Quarterly Report). These measurements were made using a beryllium foil 0.024 inches thick. The foil measurements made during this quarter predict that 58.5% of the electron beam was intercepted at the cavity. Therefore the slope, corrected for the actual beam current in the cavity, is 2.9 kilocycles per microampere. The experiments of this quarter with a 0.0012 inch thick titanium foil yielded a true slope, at 0.1 Torr, of 3.52 kilocycles per microamperes, certainly larger than previous results. However the beam geometry in the two cases is different; with the beryllium foil the beam was peaked in the center whereas with the titanium foil a uniform beam was achieved. The effect of the uniformity of the beam will be explained in Section IV.

Since the steady-state ionization equation has been derived on the assumption of geometrically uniform production of electron-ion pairs by the high energy electron beam, the experiments using the beryllium foil could not be expected to agree with the simple theory as put forth in the Sixth Quarterly report, Section III-A. Not enough data has been taken yet with the thin titanium foil to compare with previous results or with the more complete theory presented in Section IV of this report.

The various transient experiments have produced evidence for diffusion of electrons to the walls following turn-on of the high energy electron beam. The time constants involved are of the same order of magnitude as those of fundamental mode ambipolar diffusion in oxygen. Furthermore there is some evidence that the product of the time constant and pressure is a constant, as required for diffusion, although much more data still are required.

In order to make sure that the transient phenomena were not unique to the oxygen gas sample used, the cavity was filled with cylinder helium to a pressure of 0.08 Torr. A transient similar to the oxygen transient was observed. In air, the same type of transient has also been observed.

IV. DIFFUSION

A. Time-Dependent Diffusion Equation for An Attaching Gas

The attempt to relate the transient phenomena reported above with ambipolar diffusion makes necessary a careful analysis of ionization and deionization within the cavity. In particular, the time dependence of the ionization density as a function of position within the cavity must be included in the analysis. Such calculations have been performed in the past by many workers, with little opportunity for comparison of the calculation with experimental results. The simplicity of the geometry of the present experiment, however, holds out hope for something approaching a clear-cut determination of the importance of higher diffusion modes in thermal plasmas.

The differential equation for electron density is

$$(1) \quad \frac{\partial n(r,z,t)}{\partial t} = K(r,z,t) - \nu n(r,z,t) + D_a \nabla^2 n(r,z,t),$$

where n is the electron density, K is the number of electrons (and ions) produced per unit volume per unit time, ν is the three-body attachment frequency, and D_a is the ambipolar diffusion constant (c.f. First Quarterly Progress Report, pages 9-12).

The simplifying assumptions on which the derivation of this equation is based are that the presence of negative ions due to attachment does not affect the ambipolar diffusion; that there is cylindrical symmetry; that other electron loss processes are small compared to three-body attachment and diffusion; and that there are no chemical reactions taking place in the cavity. The first of these assumptions will be the subject of future work in this project.

The homogeneous part of equation (1) can be separated and solved subject to the usual boundary condition that n vanish at the walls of the cylindrical cavity. The homogeneous solution is

$$(2) \quad n_H = \sum_n \sum_m A_{nm} J_0 \left(\gamma_n \frac{r}{a} \right) \sin \frac{m\pi z}{h} e^{-\beta_{nm} t},$$

where γ_n is the n th root of J_0 , a and h are the radius and height of the cylindrical cavity, respectively,

$$(3) \quad \beta_{nm} = \nu + \frac{D}{\Lambda_{nm}^2} \frac{a}{2}, \text{ and}$$

$$(4) \quad \frac{1}{\Lambda_{nm}^2} = \frac{\gamma_n^2}{a^2} + \frac{m^2 \pi^2}{h^2}.$$

The inhomogeneous solution which satisfies the complete equation and the initial conditions is

$$(5) \quad n_I = \sum_n \sum_m B_{nm} J_0 \left(\gamma_n \frac{r}{a} \right) \sin \frac{m\pi z}{h}, \text{ where}$$

$$(6) \quad K = \sum_n \sum_m \beta_{nm} B_{nm} J_0 \left(\gamma_n \frac{r}{a} \right) \sin \frac{m\pi z}{h}.$$

The arbitrary constants B_{nm} can be found if simplifying assumptions are made about K , the electron production term. Consider the case in which the electron beam is suddenly switched into the cavity so that for $t < 0$, $K=0$, and for $t \geq 0$, K is a constant, independent of time and geometry. This closely approximates the situation in the transient experiments reported in Section III. Then at $t = 0$, $n = K$, and for all times equation (6) must hold. These considerations lead to the complete solution. With the definition $A_{nm} + B_{nm} = C_{nm}$, then

$$(7) \quad n = \sum_n \sum_m C_{nm} \left(1 - \frac{1}{\beta_{nm}} \right) J_0 \left(\gamma_n \frac{r}{a} \right) \sin \frac{m\pi z}{h} e^{-\beta_{nm} t} \\ + \sum_n \sum_m \frac{C_{nm}}{\beta_{nm}} J_0 \left(\gamma_n \frac{r}{a} \right) \sin \frac{m\pi z}{h}$$

where

$$(8) \quad \begin{cases} C_{nm} = \frac{8K}{m\gamma_n J_1(\gamma_n)} & \text{for } m \text{ odd,} \\ C_{nm} = 0 & \text{for } m \text{ even.} \end{cases}$$

From the First Quarterly Report, pages 25-27, an expression for the frequency shift of the cavity may be obtained:

$$(9) \quad \Delta f = \frac{0.1 \int_V n E^2 d\tau}{1 + (.055p)^2 \int_V E^2 d\tau}$$

For the TE_{011} mode of the rf cavity, $E \sim J_1(3.832 \frac{r}{a}) \sin \frac{\pi z}{b}$. Therefore equations (7) through (9) can be combined to produce an integral equation which will give Δf as a function of time at any given pressure. Hand computation of this problem is extremely laborious but some machine computation and some hand calculations have been made for special cases. Combining that computation with some approximations, Figures 8, 9 and 10 demonstrate the type of solutions that equations (7) through (9) produce in typical cases.

Since a great deal of data has been taken using the beryllium foil diffuser with a more or less peaked angular distribution of electrons in the incident beam, it is instructive to rederive equations (7) and (8) for the case K not constant. For simplicity let

$$(10) \quad K = k J_0(\gamma_1 \frac{r}{a}), \text{ where } K \text{ is a constant}$$

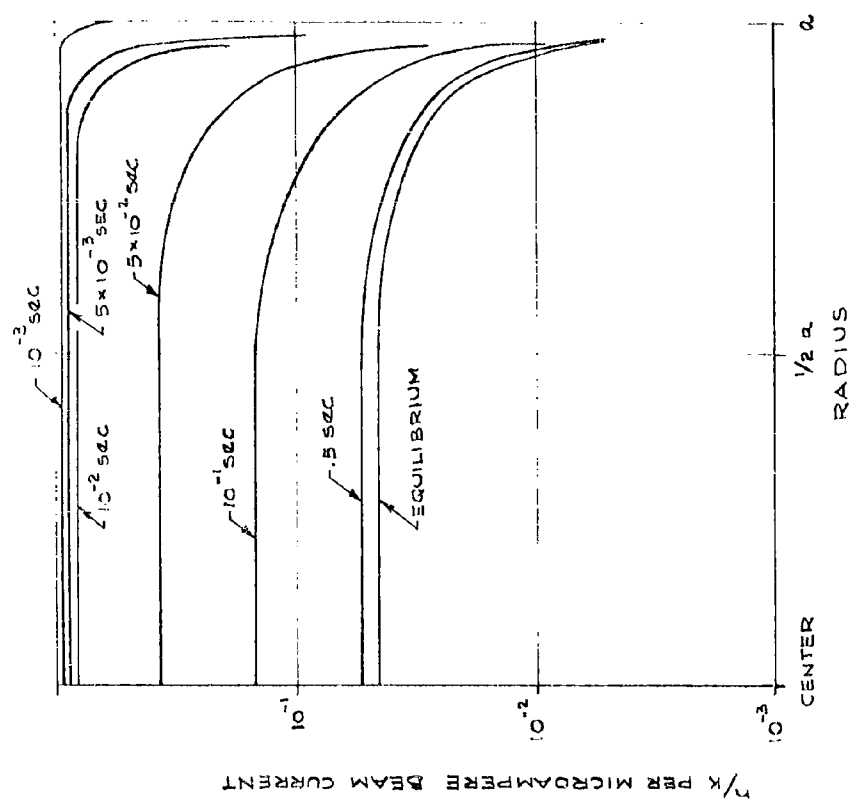


FIGURE 8
EVOLUTION OF RADIAL DISTRIBUTION OF
ELECTRON DENSITY FOLLOWING BEAM TURN-ON

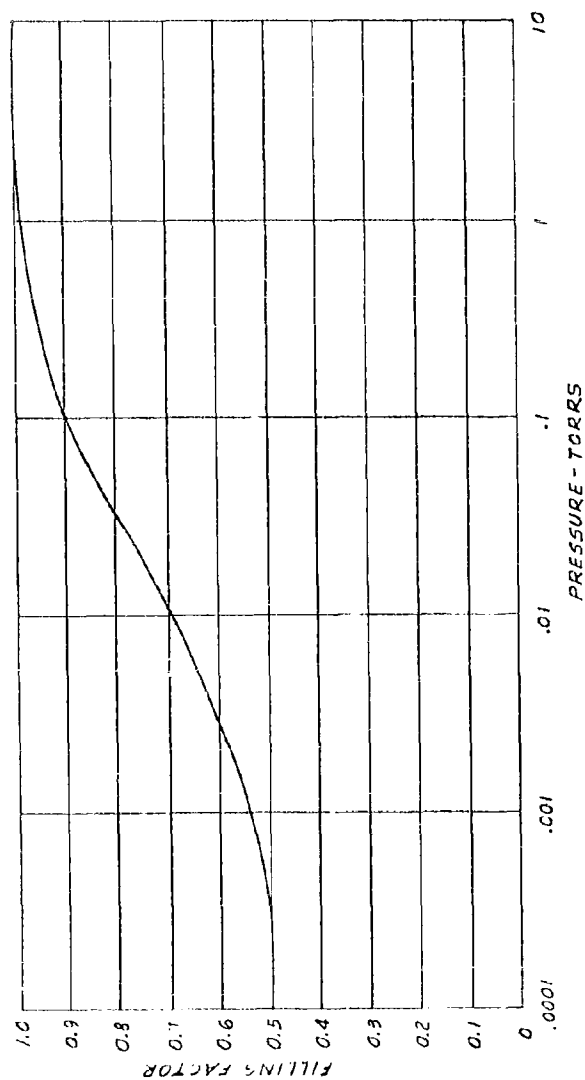


FIGURE 9
CALCULATED "FILLING FACTOR" $\int \frac{n}{n_0} E^2 dv / \int E^2 dv$ FOR OXYGEN

EQUILIBRIUM η/K PER MICROAMPERE BEAM CURRENT

24

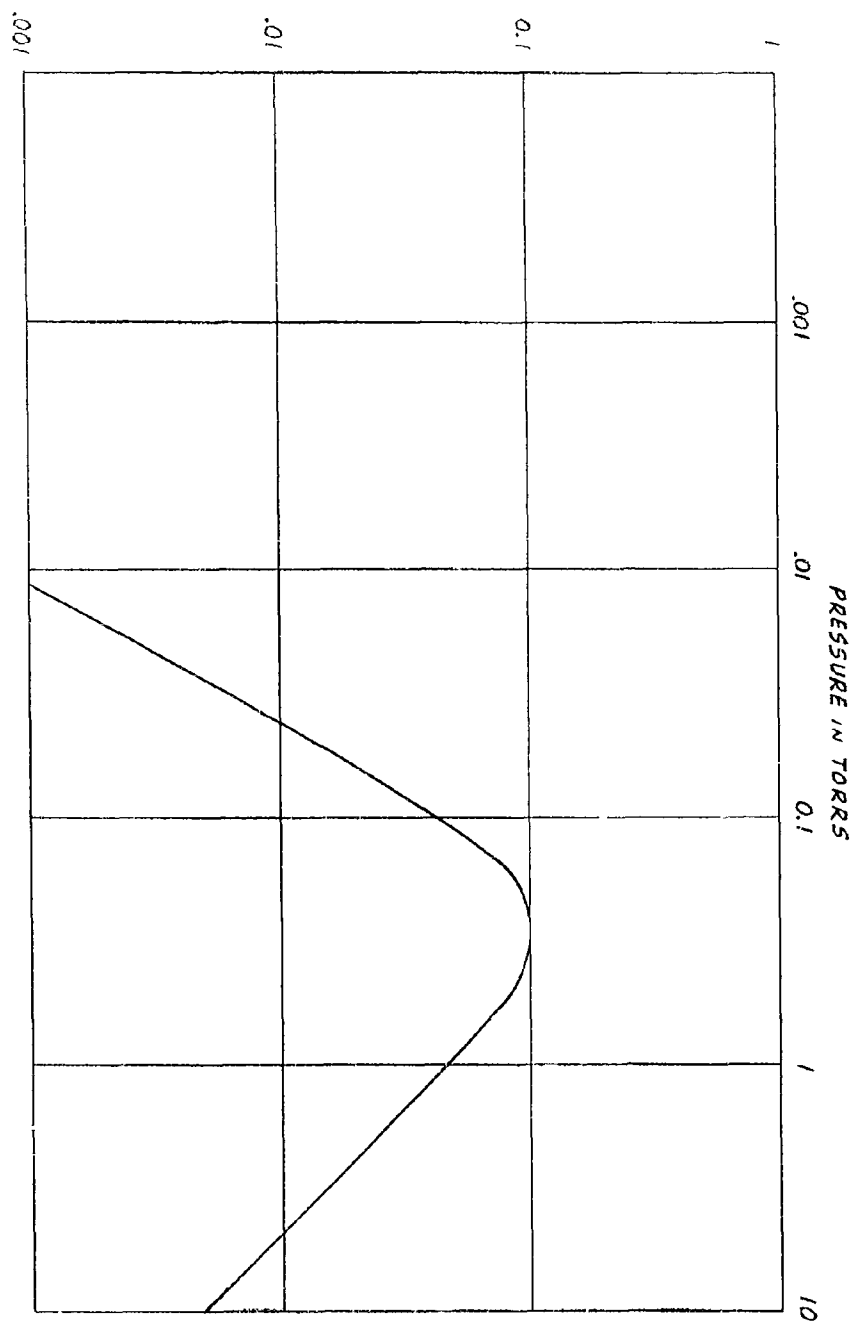


FIGURE 10
EQUILIBRIUM IONIZATION VERSUS PRESSURE
COMPUTED FROM EQUATION 7

Then at $t = 0$,

$$(11) \quad K = \sum_n \sum_m C_{nm} J_0 \left(\gamma_{na} \frac{r}{a} \right) \sin \frac{m\pi z}{h} = k J_0 \left(\gamma_{1a} \frac{r}{a} \right)$$

which has a solution for C_{nm} as follows:

$$(12) \quad \begin{cases} C_{nm} = 0 & \text{for } n \neq 1 \text{ or } m \text{ even,} \\ C_{1m} = \frac{4k}{m\pi} & \text{for } n = 1 \text{ and } m \text{ odd.} \end{cases}$$

During the next quarter, numerical solutions for this as well as for other beam geometries, will be obtained, and compared with experiments.

V. AIR MEASUREMENTS

A very interesting phenomena was observed while doing transient experiments in air. The transient associated with diffusion occurred; then, very slowly, "equilibrium" ionization density increased until a plateau was reached, many minutes later, at a value of ionization density two or three times larger than the initial density.

Figure 11 is a plot of typical time versus frequency shift experiment in air showing the change in ionization with time. It took about nine minutes for the frequency to begin to shift perceptibly, then the rise became quite steep, levelling off after about 20 minutes. The explanation for this phenomenon may possibly be found in chemical reactions. After reaching the high value of ionization, if the Van de Graaff beam is shut off for 15 minutes and then switched on again, the resulting ionization is at the high level, not the initial low value. In one case, after a two hour wait with the beam off, the ionization at turn-on was 76% of the previous peak value, and returned to that value in five minutes. This behavior is suggestive of a reversible chemical reaction which is driven by the electron beam in one direction but which slowly reverses when the beam is off the cavity.

Figure 12 is a summary of all the air data taken to this date. From Figure 12 it can be seen that the initial equilibrium ionization is higher than in oxygen, as would be expected, but not as high as would be predicted on the basis of published values for the efficiency of nitrogen as the third body in electron attachment to oxygen. In fact, on Figure 12, the experiment marked "December 19" at 0.5 Torr, has an initial slope of 2.5, very close to that of pure oxygen (2.2) and rises up to 13, about five times higher. The higher

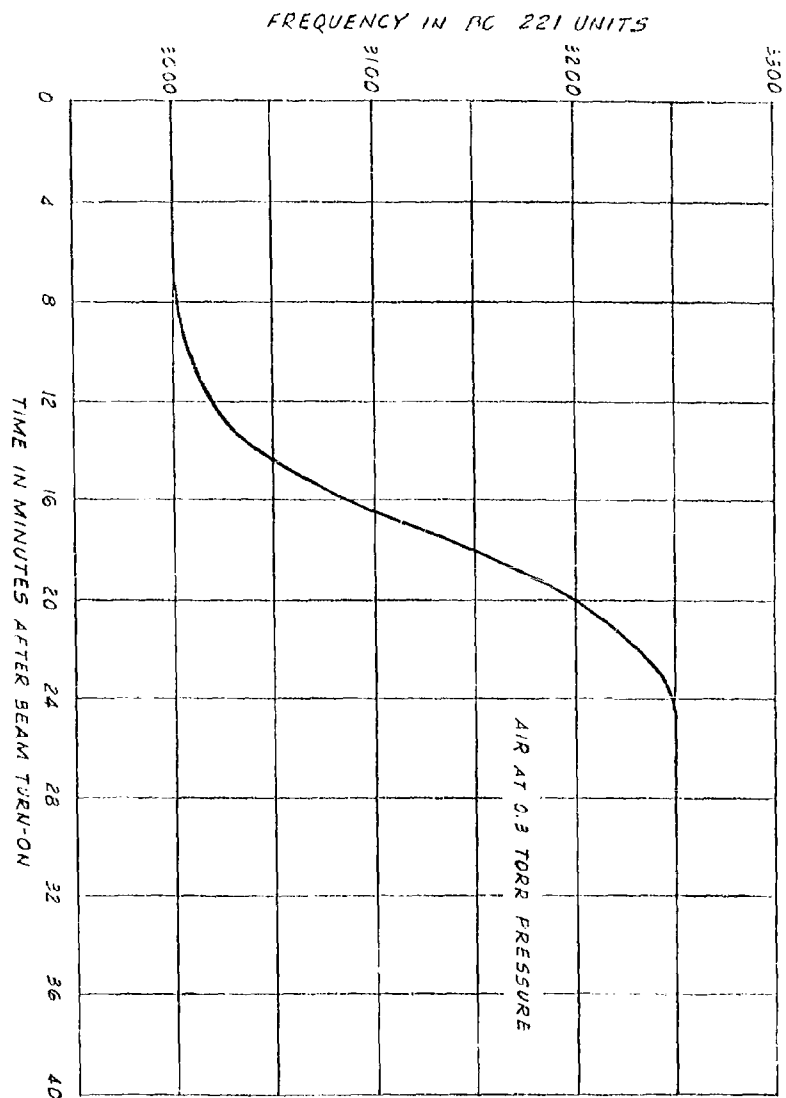


FIGURE 11
SLOW IONIZATION BUILD UP IN AIR

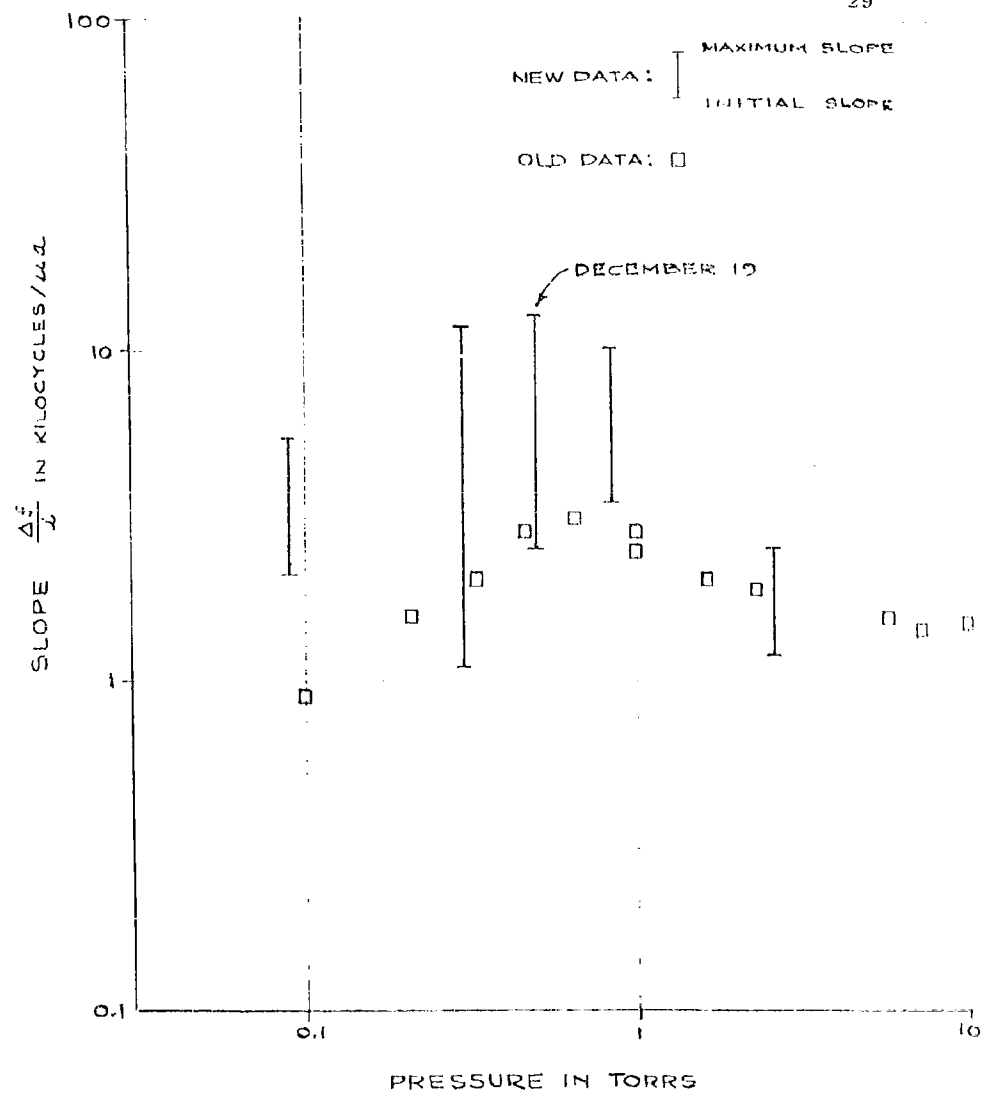


FIGURE 12
SUMMARY OF AIR DATA

values are more nearly indicative of what should be expected in air on the basis of its 20% oxygen content.

This phenomenon will be studied in more detail in the next quarter. In particular various $N_2 - O_2$ concentration ratios will be studied to unravel the chemistry.

VI. PLANS FOR NEXT QUARTER

During the next quarter, enough data should be accumulated in oxygen to permit a complete analysis of the linear loss processes (that is, attachment and diffusion) in the regime of operating conditions employed in this work. Measurements in nitrogen and oxygen-nitrogen mixtures will be begun in detail, to determine the normal behavior of the mixtures and to search for radiation chemistry effects. The detailed calculation of the diffusion transient accompanying beam turn-on will be completed, and results compared with experiment.

In addition, a new dimension will be added to the measurement program during the quarter. An rf mass spectrometer will be designed and built, and probably attached to the cavity within the period. The spectrometer will be capable of observation of both positive and negative ions produced in the cavity. The addition of an internal ionizer, to permit studies of neutral molecules, has been delayed until the spectrometer itself is operative.

VI. DISTRIBUTION LIST

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Department of Physics
University of Pittsburgh
Pittsburgh 13, Pennsylvania (1)

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Department of Physics
The Johns Hopkins University
Baltimore 18, Maryland (1)